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Performance study of solar photovoltaic-thermal collector for domestic hot water use and thermochemical sorption seasonal storage

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Abstract

To maximise the utilisation of solar energy and improve the solar fraction for domestic applications, this paper explored the potential of the hybrid solar Photovoltaic/Thermal (PV/T) collector integrated with a thermochemical sorption thermal storage system. The thermal output was used to provide domestic hot water or stored over seasons in the England city of Newcastle upon Tyne. The performance of the water-cooled PV/T collectors with or without an air insulation layer between the glass cover and the Photovoltaic (PV) cell was compared. The electrical power generation model of the PV cell developed in MATLAB was coupled with a Computational Fluid Dynamics (CFD) model to simulate the simultaneous generation of electrical and thermal energy. The one-diode model was used to simulate the electrical production of the PV cell with the new correlations of the series resistance and the shunt resistance proposed in this work, so that the accuracy of dynamic performance simulation can be improved especially in the cases with relatively higher PV cell temperature. The water outlet temperature was studied at 100 °C to meet the heat supply requirement of the sorption cycle using the working pair strontium chloride-ammonia. It was found that the PV/T collector with air gap could produce ~~133-28~~ liter hot water per day per m² collector (L/(day·m²)) with the electric efficiency of about 10% if the water outlet temperature was required at 100 °C; in contrast, around ~~28-133~~ L/(day·m²) was produced with the electric efficiency of 13% when the water outlet temperature at 40 °C. The PV/T collector without air gap was not competent for the applications studied in this work especially in cold regions. The application case studies suggested that an installation of 26 m² air-gap PV/T collectors integrated with the strontium chloride-ammonia thermochemical sorption storage system can fully satisfy the annual hot water demand of an ordinary single household in Newcastle upon Tyne with 100% solar sources, and cover at least half of the annual electricity consumption.

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25 **Keywords:** solar energy; photovoltaic-thermal collector; domestic hot water use; seasonal thermal energy
26 storage; CFD simulation, thermochemical sorption

27

28 **Nomenclature**

29 *Abbreviations*

30	CFD	computational fluid dynamics
31	HTF	heat transfer fluid
32	PCM	Phase change material
33	PV	photovoltaic
34	PV/T	photovoltaic/thermal
35	PV/T-AG	photovoltaic/thermal collector with air gap
36	PV/T-no-AG	photovoltaic/thermal collector without air gap
37	STC	standard test condition

38 *Symbols*

39	C_p	specific heat capacity (J/(kg·K))
40	E_g	band-gap energy of semiconductor used in PV-cell (eV)
41	g	gravity (m/s ²)
42	G	solar irradiance (kW/m ²)
43	Gr	Grashof Number (-)
44	I	electrical current (A)
45	n	PV-cell ideal factor (-)

46	N	number of the PV-cell in PV-panel (-)
47	Nu	Nusselt number (-)
48	N_e	clear sky factor [8 for clear; 0 for totally covered]
49	k	Boltzmann's constant (1.38×10^{-23} J/K)
50	k	thermal conductivity (W/(m·K))
51	K_i	PV-cell's short-circuit current temperature coefficient (A/K)
52	Pr	Prandtl number (-)
53	q	electron charge (1.6×10^{-19} C)
54	R	resistance (Ω)
55	Ra	Rayleigh number (-)
56	T	temperature (K)
57	V	voltage (V)
58	<i>Greek letters</i>	
59	α	absorptivity (-)
60	β	thermal expansion coefficient (K^{-1})
61	δ	thickness (m)
62	ε	emissivity (-)
63	μ	dynamic viscosity (Pa·s)
64	ν	kinematic viscosity (m/s^2)
65	ρ	density (kg/m^3)

66	σ	Stefan Boltzmann constant ($5.670367 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$)
67	τ	transmissivity (-)
68	<i>Subscripts</i>	
69	ab	absorber
70	conv	convection
71	con_T	constant of linear variation on temperature difference
72	con_G	constant of linear variation on irradiance difference
73	D	diode (current)
74	eq	equilibrium
75	g	glass
76	gr	ground
77	MPP	maximum power point
78	oc	open-circuit
79	p	parallel
80	pv	photovoltaic
81	PH	photo (current)
82	ray	radiation
83	RS	reverse saturation
84	s	series
85	S	saturation

86 SC short circuit

87 SH shunt

88 STC standard test condition

89 t thermal

90 v ambient vapour

91 wi wind

92

93 1. Introduction

94 Solar energy is one of renewable energy sources that is highly untapped and underutilized. The amount of solar
95 radiation incident on the roof of a typical home exceeds its energy consumption over a year, but it is a pattern
96 completely opposite to the heat demand pattern and it has large summer-to-winter variations and significant diurnal
97 variations. It is imperative to integrate energy storage unit in order to overcome the seasonal discrepancy between
98 demand and supply and substantially increase the solar fraction of energy supply. Especially for medium and high
99 latitude regions like the UK where the energy consumption for space heating and hot water use accounts for around
100 80% of the total domestic final energy consumption [1]. Since around 80% heating is provided by natural gas,
101 there is a factor of approximately four variance between a winter peak gas demand and a summer demand. That
102 indicates the enormous range potential required for seasonal solar heat energy storage [1]. On the other hand,
103 hybrid PV/T systems incorporating two methods of energy conversion, i.e. photo-thermal and photo-electric
104 conversion in one device, have received great attention for the improved energy utilization efficiency of solar
105 sources for the past few years. It kills two birds in one stone as the thermal energy absorbed by the solar PV cell
106 is transferred to the cooling fluid (air or liquid) through the integrated collector and used for heat applications such
107 as space heating, domestic hot water, drying, etc.; consequently, it contributes to a lower PV cell working
108 temperature for the improvement in electrical conversion efficiency [2, 3].

109 The hybrid PV/T has undergone rapid developments in recent decades. To maximise the conversion and utilisation
110 of solar energy, many research works have primarily targeted thermal energy production and applications, as the
111 PV panel could extract maximum of 25% of photon energy from a solar spectrum of AM1.5G while the remaining
112 75% is thermal energy [3]. Apart from the most influential external factors to energy conversion efficiencies such
113 as geographical location and climate (including solar irradiance, ambient temperature, wind speed, etc.), the R&D
114 efforts on the thermal production of hybrid PV/T systems have been mainly on the factors including the cooling
115 fluid type, the design configuration and parameters of thermal collectors, in addition to operating parameters such
116 as fluid flow rate and the type of application used, as the former two factors are the most important elements
117 discussed in majority of research works. Commonly used coolants are air [4, 5] and water [4, 6-8], or a mix of the
118 two [9, 10]. Since water has high specific heat capacity and density compared with air, the water-based hybrid
119 PV/Ts achieve higher thermal and electrical efficiency than air-based ones [4, 5, 11]; moreover, the use of water
120 as working fluid is more suitable for heating applications like space heating, especially domestic hot water use, or
121 as efficient heat carry and transfer media for other downstream applications. In recent decade, there is a strong
122 motivation to use different nanofluids (a mixture of base fluid like water or ethylene glycol, and nanoparticles) to
123 improve the heat transfer performance and hence both electric and thermal efficiencies of the hybrid PV/T system,
124 as nanofluids have intensified thermophysical properties, such as thermal conductivity, viscosity, and convective
125 heat transfer coefficients compared with conventional fluids [12-15]. The drawbacks of using nanofluids are
126 associated with high cost of nanoparticles, limited time of stability, and pressure drop in the collector. Apart from
127 the efforts on nanofluids, incorporating PCM within the PV/T system as a heat sink is another prevailing research
128 topic for efficiency improvement of the PV/T system in recent decade. Works proposed to add a PCM layer
129 beneath the absorber [16], or employ microencapsulated PCM slurry [17], or embed PCM in the hot water tank
130 [18], etc. Depending on the melting temperature of the PCM, although it has limited effect on reducing the PV cell
131 temperature with limited cooling rate compared to water cooling system, it can effectively stabilise the transferred
132 heat and prolong the duration of the stabilised heat delivery with its high latent heat storage capacity, which could
133 significantly improve the electric output and mitigate the thermal fatigue by limiting the peak temperature of the
134 PV cell when the solar irradiance is the richest. Many PV/T systems with PCM also worked with addition of air
135 or water or nanofluid cooling to further improve the thermal energy recovery [19, 20].

136 The collectors may have a typical sheet-and-tube (flat plate parallel tubes type, or serpentine tube type, etc.)
137 configuration [6, 21], flat-box-type [6, 22, 23], or heat pipe [24-26], etc. The design of unglazed or glazed (with
138 different numbers of glazing covers) [6, 13, 27, 28] and different packing factor [26, 28-30] have significant overall
139 effect. The box-structure collector, may be built from extruded aluminum alloy or made of polycarbonate material,
140 has been reported to provide higher heat transfer and achieve higher final water-temperature and higher energy
141 efficiency even in the thermosyphon design than the sheet-and-tube collectors [6, 31, 32]; however, the latter one
142 is the most common and a highly appropriate option for domestic application of water-based PV/T due to high
143 efficiency (marginally lower than that of the flat-box design [6]), easiest and most affordable configuration to
144 manufacture as it relies on well-known, readily available technology [6, 21, 30]. The heat pipe combined PV/T
145 design is one of effective solutions to ensure the uniform temperature of PV panel without the need of water pump,
146 and to avoid freezing in cold regions. It has been studied for application of building integrated PV/T system
147 (BIPV/T) [33], or integrated within the building envelop (BIPV) [34], but with modest electric efficiency (less
148 than 10%) in most cases [2]. The glazed type PV/T is the better choice than the unglazed one if the target is to
149 acquire more thermal output and higher overall energy efficiency, but the addition of glass covers results in higher
150 optical losses, leading to electric efficiency decrease [4, 6, 27, 28]. The packing factor is an important parameter
151 in PV/T system design, and the effect of its variation on the PV/T performance strongly depends on different PV/T
152 configuration with different coolant types. Many works concluded that higher packing factors were desirable in
153 order to maximize electrical output, but not a favorable factor for the thermal production; nevertheless, in the work
154 [26], increasing packing factor caused higher PV panel temperature, leading to higher thermal efficiency but
155 reversely the decreased electric efficiency; in the air-cooled collector system with double glass layer design
156 reported in [35], the electric efficiency decreased with the increase of the packing factor, both the annual gain of
157 electric output and thermal output was decreased. The double glass layer design significantly contributed to the
158 higher PV panel temperature and considerable optical loss compared to unglazed or single glass cover, however,
159 the increment of thermal production due to the higher PV module temperature may not offset the reduced heat
160 gain attributed to the lower packing factor within the double glass cover design. Additionally, panels connection
161 in series favors in thermal energy efficiency, whereas it reduces when panels are connected in parallel [36].

162 The hybrid PV/T has undergone rapid development, and there is still research gaps and the remaining questions
163 or unexplored areas to be addressed further. For example, (1) majority of works on flat-plate water-based PV/T
164 focused on low temperature application ($<60\text{ }^{\circ}\text{C}$), such as space heating (air heating or radiant floor heating, $<40\text{ }^{\circ}\text{C}$)
165 and domestic hot water use ($40\sim60\text{ }^{\circ}\text{C}$) in the context of warm or hot regions with the ambient temperatures in
166 the range of $30\sim37\text{ }^{\circ}\text{C}$, which could be problematic yet rarely explored for cold regions with lower solar irradiance
167 and lower ambient temperature. (2) Even for hot climate, there is scarce information on medium temperature
168 application ($>60\text{ }^{\circ}\text{C}$). Considering to harness the recovered heat for downstream applications, the quality and
169 quantity of thermal production are both important to meet the operating requirement of the downstream
170 applications. (3) Moreover, most works dealt with thermal efficiency and the improved electric efficiency during
171 the daylight only, the benefit of storing thermal energy transferred from the PV/T system for various applications
172 after sunset has hardly been explored [2].

173 Dubey and Tiwari [37] numerically studied the energy yield by 2~10 flat-plate water-based PV/T collectors (the
174 packing factor 0.0825) connected in series under the Indian weather conditions. When the solar intensity was
175 $600\sim850\text{ W/m}^2$ and the ambient temperature $30\sim37\text{ }^{\circ}\text{C}$, 10 series-connected collectors produced hot water at outlet
176 temperature max. $85\text{ }^{\circ}\text{C}$ at a constant flow rate 0.04 kg/s with the electrical efficiency of $8.7\%\sim10.5\%$. In the case
177 of coupling with a water storage tank (200 L) and the flow rate was fixed at 0.01 kg/s , the maximum temperature
178 was achieved around $95\text{ }^{\circ}\text{C}$. Ibrahim et al. [38] studied a PV panel combined with rectangular-tube spiral flow
179 absorber to produce hot water in a storage tank up to $50\text{ }^{\circ}\text{C}$ in the Malaysian tropical climate (ambient temperature
180 around $35\text{ }^{\circ}\text{C}$). Because of the increasing temperature of inlet water in a closed water loop, thermal and electrical
181 efficiencies were decreasing throughout the day and the average values were 48% and 10.8%, respectively. Rosa-
182 Clot et al. [39] experimented a PV/T collector called TESPI, in which a thin layer of water flowing in a
183 polycarbonate box that was simply put on the top of the PV panel. When three collectors were series-connected,
184 the outlet water temperature reached up to $60\text{ }^{\circ}\text{C}$ in an open loop in some September days as the ambient
185 temperature at around $30\text{ }^{\circ}\text{C}$. The total loss of electric power comparing the PV/T collector with the reference PV
186 panel was on average 10.7%. Herrando et al. assessed the suitability of a single-cover sheet-and-tube PV/T system
187 [30] and a polymeric flat-box PV/T system [23] for the provision of electricity and hot water for a typical house

188 in London (low solar irradiance and low ambient temperature). The packing factor of the solar collector and the
189 collector flow rate were specifically considered to estimate the performance of the PV/T system, and it was
190 concluded that the coolant flow rate did not strongly influence the electrical output but affected the hot water
191 output, while the packing factor affected the electrical output considerably more than it did the thermal equivalent.
192 It is worth noting that although using higher coolant flow rate increases thermal efficiency, the outlet temperature
193 of the coolant is lower, therefore requiring a greater use of auxiliary heater to further heat it to 60 °C for the
194 domestic hot water use. Since it is not possible to maximise both outputs at the same time, a trade-off is needed
195 depending on the end-user needs. It was suggested high packing factor (0.8~1) and low coolant flow rate as being
196 appropriate in terms of adequately covering both the electrical and thermal demands. The results shown that a 15
197 m² sheet-and-tube PV/T system studied with a completely covered collector and a flow rate of 20L/h, can cover
198 51% of the total electricity demand and 36% of the total hot water demand over a year [30]; 11 flat-box PVT
199 collectors together with a 0.83 m³ storage tank and a constant flow-rate of 30 L/h can cover 66% of the electrical
200 and 29% of the thermal energy demands annually [23]. Hazami et al. [40] studied the monthly and annually
201 performance of the SCS (Solar CombiSystem with water storage tank) with a unit module area of 1.42 m² for the
202 space heating load (floor heating at around 24 °C) and domestic hot water supply (at 60 °C) and the electric energy
203 production for a 120 m² building occupied by 4-5 occupants. There was a shortage of thermal energy production
204 in cold months from November to March, during which the SCS provided from 40 to 70% of the total domestic
205 hot water needs, whereas the SCS provided about 150% of the total energy needs in hot months. Such a system
206 allows the preservation of about 48% of electric energy supplied by the national grid, or permits the saving of
207 about 46% of gas/gas town consumed by a gas boiler of water heating. To further achieve a net/near zero energy
208 status for existing houses, a seasonal storage system was suggested the most appropriate solution to store the
209 excess of energy. García et al. [41] studied the possibility of combining a heat pump supported PV/T system with
210 a low temperature district heating network in three different configurations for a Central European multi-family
211 house. PV/T systems provides one more solution towards low carbon and eventually zero carbon buildings, for
212 example, the PV/T system in the hybrid configuration studied produced 34% of the heat and 55% of the electricity
213 demand of the building, which reduced its carbon footprint by roughly 50%. In terms of energy efficiency and
214 profitability, the key was to effectively manage the excessive heat production of the PV/T system that cannot be

215 exploited in the building, either through reliable seasonable thermal energy storage with minimum energy loss or
216 feeding into the district heating network. The accessibility to a low temperature district network is currently still
217 very low everywhere and requires larger scale of retrofitting effort than constructing a stand-alone thermal energy
218 storage system.

219 To maximise the utilisation of solar energy and minimise the interaction of PV/T systems with national grid,
220 especially exporting electricity which strongly relies on the grid accommodation capacity, the varying regulation
221 and government incentives, and with the district heating network (as foregoing), the scalable and efficient
222 seasonable thermal energy storage system is one of the most promising solutions to be integrated with the PV/T
223 systems, which has been for the first time explored in this work. The seasonal solar energy storage system
224 conceived in this work innovatively integrated with the PV/T collector is the most promising long-term storage
225 method due to its zero-loss and much higher thermal energy density than the hot water tank in the above mentioned
226 studies and latent heat storage. More comprehensive knowledge and information about thermochemical sorption
227 technology and the comparison between different seasonal storage technologies can be found in review articles
228 [42-48]. Ma et al. [49] explored the feasibility of applying different technologies of seasonal solar thermal energy
229 storage in domestic dwelling in the UK, and estimated the volume of a sorption storage system to satisfy 100%
230 solar fraction was 31.5~44.3 m³ for different UK cities studied, in contrast with the water storage system that
231 required a volume of 107~150 m³. However, such an integration requires relatively demanding operational
232 condition, energy charging process through the endothermic desorption happens at comparatively higher
233 temperature than the hot water use reported in the above studies, for example, the typical working pair
234 SrCl₂/ammonia has the equilibrium desorption temperature at around 95 °C, respectively when heat sink
235 temperature at 30 °C. The closed water loop cannot be considered in this situation, because the return water from
236 thermochemical system still has relatively high temperature, which is detrimental for both electrical and thermal
237 efficiency. Therefore, with an open loop water heating, this work investigated the energy output and efficiencies
238 of a PV/T collector that produces relatively high temperature hot water to be used for thermochemical sorption
239 cycles. The most common and mature design of the PV/T collector, a completely PV panel-covered sheet-and-
240 tube PV/T collector with single glass cover and an air insulation layer between the glass cover and the PV panel,

241 was considered as a highly suitable starting point towards the target of thermal production as priority at a
242 reasonable cost. Unlike the above studies using fixed flow rate of the heat removal fluid, water flow rate was
243 adjusted in the current work depending on the variable solar irradiation to achieve the required temperature
244 threshold for the thermochemical process. Using a CFD model coupled with a detailed PV panel model and the
245 real weather data of the city of Newcastle upon Tyne in the UK, dynamic performance of the PV/T collector was
246 numerically and parametrically investigated to explore the potential of such a novel integrated system for seasonal
247 solar storage application in the England climate. The influence of the varying water flow rate and the high
248 temperature of water output on the efficiencies of the PV/T collector was also analyzed and discussed.

249

250 **2. Working principles**

251 **2.1. PV/T solar collector**

252 Solar radiation that reaches the PV layer is absorbed in two forms, electricity and heat. A portion of visible light
253 waves was absorbed to produce electrical current; infrared and the rest of visible light waves are mostly absorbed
254 in the form of heat and transferred to neighbouring layers: conductive heat transfer to the absorber eventually
255 extracted by the heat transfer fluid (HTF) flowing through the tubes, natural convective heat transfer to the air gap
256 layer and radiative heat transfer to the glass cover layer. Further radiative heat transfers from the glass cover layer
257 to sky and ground is also considered in some studies pursuing highly accurate results [50]. The impact of the glass
258 encapsulation and the adhesive layer on the heat transfer can be neglected due to their very thin thickness,
259 negligible thermal mass and good heat transfer properties.

260 [Figure 1](#) shows a typical sheet-and-tube photovoltaic-thermal collector studied in this work, which consists
261 of a single glass cover, PV-cells, tubes, HTF (inside the tubes), and insulation. Many developed configuration of
262 flat plate PV/T collectors differ from each other, like unglazed or glass-covered PV cell with or without an air gap
263 between the glass cover and the PV cell, coupled with an air-based, or water-based or bio-fluid thermal collector.
264 Unglazed design is more favourable if the electrical power generation is of priority, which allows quick heat
265 dissipation of the PV cell through natural convection, leading to improved electrical conversion but compromised
266 thermal efficiency. On the contrary, a glass cover generates optical loss and prevent natural ventilation, resulting

267 in the reduction of PV cell performance, whereas, the glass cover strongly increase the thermal performance of the
 268 thermal collector, leading to a better overall thermal energy conversion [51]. An air gap acts as a thermal insulator
 269 to prevent the conduction heat transfer between the PV cell and glass cover layers, it is normally used to minimize
 270 the heat loss and further enhance the thermal performance especially targeting comparatively higher output
 271 temperature. Water-based collector is studied in this work due to its greater heat transfer properties [52] compared
 272 to air-based system, and a water tank is used to collect and store the thermal output from the PV/T collector for
 273 other applications that require relatively higher temperature heat, such as domestic hot water use ($>50\text{ }^{\circ}\text{C}$) or
 274 thermochemical storage ($>70\text{ }^{\circ}\text{C}$), as shown in [Figure 2](#) of the system schematic.

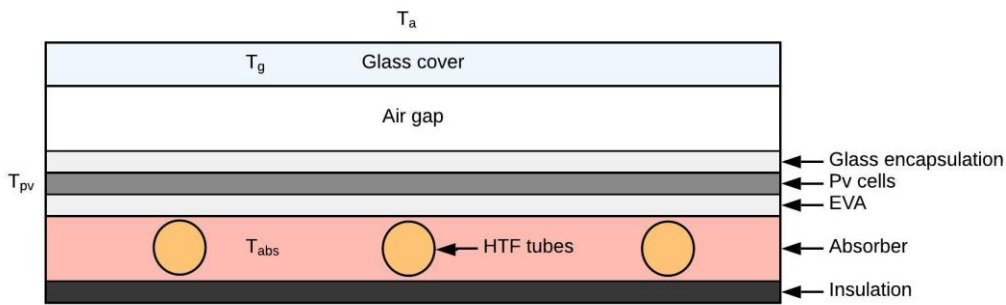


Figure 1. A typical flat plate glass-covered water PV/T collector

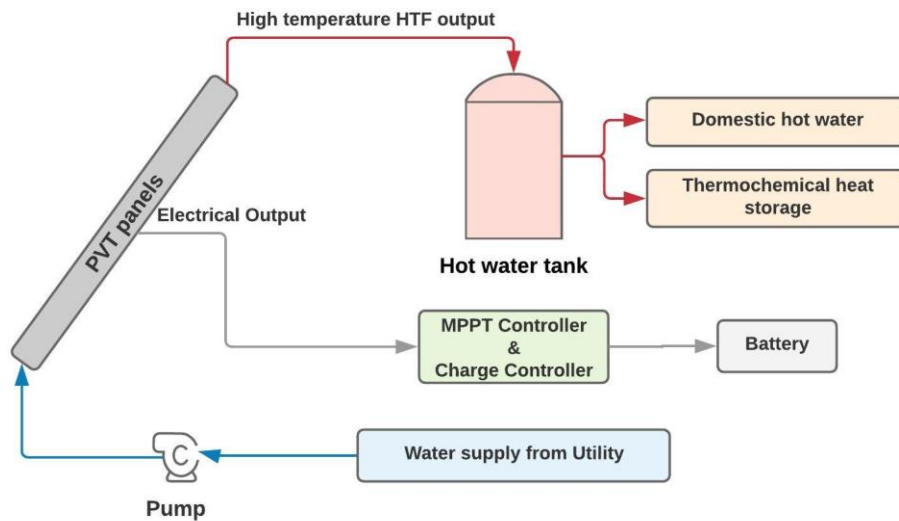
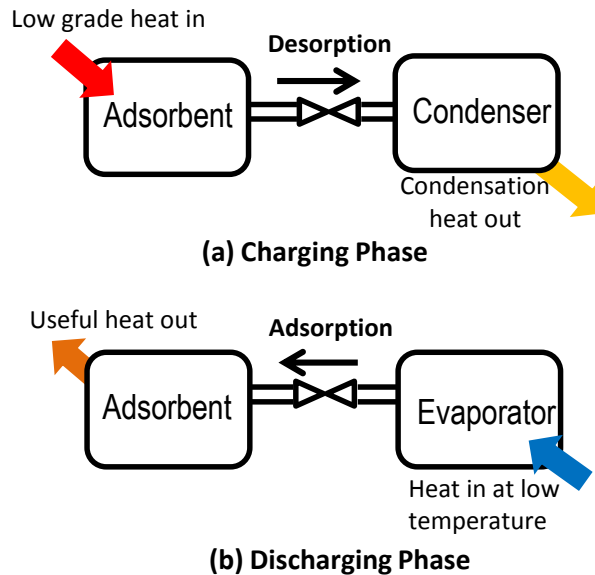


Figure 2. System schematic

280

281 2.2. Thermochemical sorption storage

282 A basic thermochemical sorption system comprises two vessels, one contains adsorbent material, the other one is
 283 filled with liquid/vapour refrigerant as the condenser/evaporator as shown in [Figure 3](#)~~Figure 3~~. The
 284 thermochemical sorption cycle uses the reversible reaction between adsorbents like halide salt amines and the
 285 refrigerant like ammonia to realise the energy charging and discharging process. During the charging process, the
 286 salt ammine adsorbent is heated to desorb refrigerant vapour which gets cooled down and condenses in the
 287 condenser, thus the thermal energy is stored in the form of chemical potential without energy loss for long term
 288 storage. In the discharging phase, the liquid refrigerant extracts heat from the available heat source (i.e. ambient
 289 air, river or lake or ground water) and evaporates, while the salt ammine adsorbent adsorbs the refrigerant vapour
 290 and releases considerable amount of adsorption heat for heating purpose.

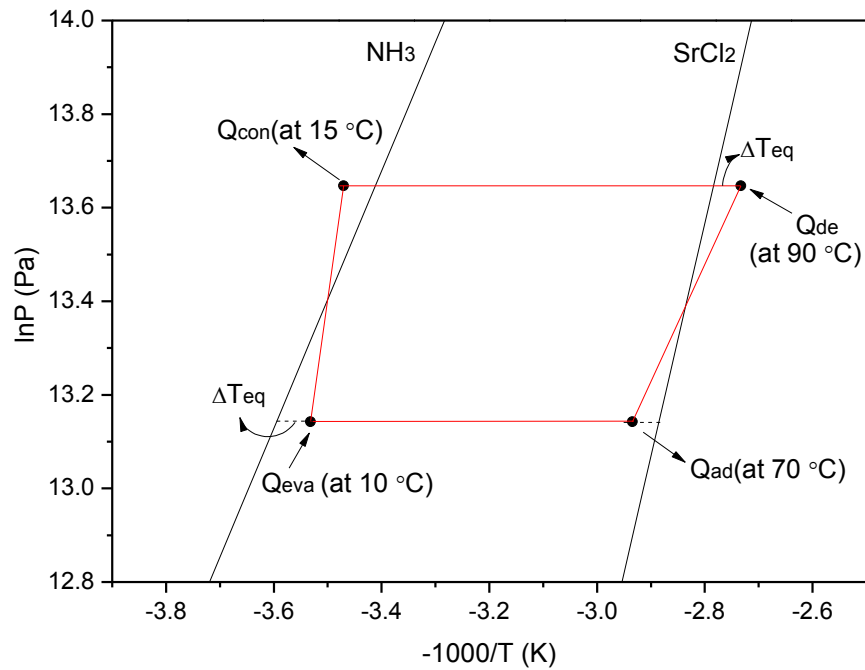


291
292

Figure 3. A basic thermochemical sorption cycle for energy storage.

293 The typical working pair of $\text{SrCl}_2\text{-NH}_3$ was applied in this work to be integrated with the PV/T-AG collector for
 294 solar thermal seasonal storage. The chemical reaction between the SrCl_2 ammine and ammonia is expressed in Eq.
 295 [\(1\)](#)~~(1)~~, and the studied cycle depicted in the P-T diagram is shown in [Figure 4](#)~~Figure 4~~. The hot water output from
 296 the PV/T-AG collector was used for desorption process in the charging phase. For example, when the average
 297 condensation temperature is around 15 °C by air-cool method, the required desorption temperature should be at

298 least around 90 °C with an equilibrium temperature drop of 5 °C. The equilibrium drop is defined as the difference
 299 between the equilibrium condition and its actual state, which is the main driving force of the chemical reaction
 300 [53]. That suggests the PV/T-AG collector should produce hot water at around 100 °C if there exists a heat transfer
 301 difference of 10 °C. It should be noted that after the hot water supplies heat to the thermochemical sorption system
 302 it goes to the water tank as its temperature is still sufficiently high for domestic hot water use. In the discharging
 303 phase, the system runs as a water source heat pump, refrigerant evaporator extracts heat from the water source that
 304 has more stable and higher temperature (typically 10 °C in the winter) than the ambient air, in the meantime, the
 305 adsorption heat is required at least 70 °C to provide proper domestic hot water (at around 60 °C), with a heat
 306 transfer temperature difference of around 10 °C.



307
 308 Figure 4. The thermochemical sorption cycle using working pair $\text{SrCl}_2\text{-NH}_3$ in the P-T diagram.

309

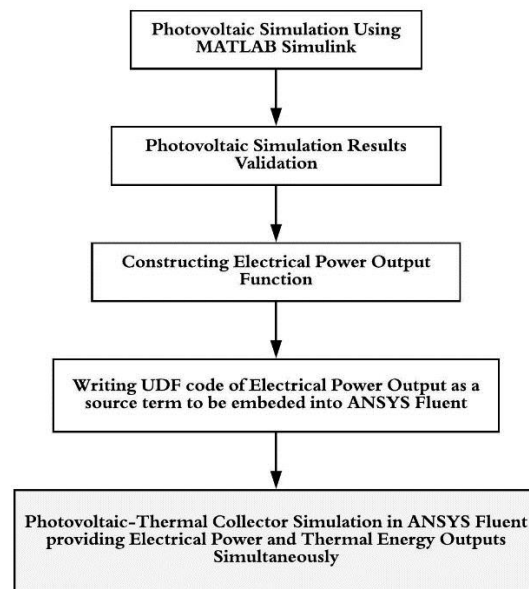
310 3. Modelling and simulation

311 The overall performance of the PV/T system including electricity and thermal output depends on the solar energy
 312 input, the ambient temperature, wind speed, the operating temperature of the system parts and the heat extraction
 313 conditions such as the inlet and outlet temperature and the mass flow rate of the HTF. Two different designs of
 314 the single glass-covered sheet-and-tube PV/T collectors, with and without airgap, have been analysed and

315 compared with the reference PV module to reveal more insights. PV/T collectors without airgap are already
316 available off-the-shelf, and measurement data is easily available for model validations in this work. The weather
317 data in 30-minute time step from sunrise to sunset of Newcastle-upon-Tyne, a representative high-latitude city in
318 the UK, including atmospheric temperature, global horizontal radiation and wind speed, is available from the
319 software Meteonorm.

320 Unlike majority of the reported systems coupled with a water tank, which used a closed loop as the inlet water
321 temperature of the PV/T collector was gradually increasing throughout the process since the water temperature in
322 the tank was increasing, in this work it was an open loop of water circulation with a fixed inlet temperature (i.e. at
323 the ambient temperature) and a certain temperature threshold of the outlet water in order to meet the requirement
324 of the downstream application (e.g. 60 °C for hot water use, >70 °C for thermochemical storage). In this instance,
325 according to the varying weather conditions, the mass flow rate of the water should be adjusted to ensure the
326 required outlet water temperature, instead of a fixed value of the HTF flow rate. Therefore, it is important to study
327 the influence of such operating conditions on the individual electrical and thermal efficiency and the overall energy
328 conversion efficiency of the PV/T collector and gain insights of the potential of the PV/T collector integrated with
329 thermochemical sorption system.

330 The temperature variation profile of the system components was simulated and analyzed in ANSYS Fluent coupled
 331 with a detailed model of the PV cell developed in the Matlab. The methodology to simulate the simultaneous
 332 generation of electrical power and thermal power from the PV/T collector is illustrated in [Figure 5](#). A one-
 333 diode current-voltage (I-V) model was developed using Matlab Simulink to represent the relationship between the
 334 electrical generation performance of the PV cell and the varying solar irradiance and cell temperature when the
 335 load voltage varies from 0 to open circuit voltages. The measured data of Siemens SM46 PV module and Solarex
 336 MSX60 PV module presents the current-voltage characteristics under the standard test condition (STC, i.e. the PV
 337 cell temperature at 25 °C and the irradiance of 1,000 W/m²) was used to validated the PV cell model. To assure
 338 the generic application of the I-V model developed in this work it was also verified against the measured data of
 339 the Solarex MSX-60 PV module at the irradiance of 1,000 W/m² and temperature ranges from 0 to 75 °C in addition
 340 to the STC. Since there is little information reported for a full set of experimental data on the PV/T collectors, the
 341 thermal analysis model were also validated using the measured PV cell temperature of the same commercial PV
 342 modules.



343
 344 Figure 5. The methodology of simultaneous simulation of electrical and thermal energy in the photovoltaic
 345 containing panels.

346

347 3.1. PV cell model development and validation

348 Instead of the simplified expression of electrical efficiency reported in Ref.[54] which was extensively used for
349 the PV/T research works [55], the one-diode model [56] (Figure 4) was used to simulate the electrical production
350 of the PV cell with significantly improved accuracy of dynamic performance. Kirchhoff's current law is used at
351 the circuit node of the photocurrent output (I_{PH}) in ~~Figure 6~~ (a) and (b), which states that the summation
352 of currents at any circuit nodes is zero.

353 A PV panel consists of a number of the PV cell connected in series (N_s cells) and parallel (N_p lines) as represented
354 by the diodes in ~~Figure 6~~ (a). In majority of the previous research works, the ideal conditions was assumed
355 as shown in ~~Figure 6~~ (a) as all PV cells were perfectly manufactured and there was no internal resistance
356 through the wiring between the PV cells. However, for a more accurate model, the wiring resistance between PV
357 cells and the recombination loss between the P-N junctions of PV cells should be taken into account, which are
358 represented as R_s and R_{SH} , respectively, in ~~Figure 6~~ (b), where the I_D represents the combined diode
359 currents of those shown in Figure 6(a). The current (I) that passes through R_s and goes to the load can be expressed
360 in Eq. ~~(2)~~ which is the output current of the PV panel. I_{PH} is the photo current generated from the doped
361 semiconductor used in the PV cells, and it varies depending on the PV cell temperature and the solar irradiance
362 and can be calculated from Eq. ~~(3)~~. The I_D in ~~Figure 6~~ (b) is calculated from Eq. ~~(4)~~. I_{SH} is the shunt
363 current obtained from Eq. ~~(5)~~. The elements in Eqs. ~~(3)~~ - ~~(5)~~ to calculate currents are the characteristics
364 of the PV cell material, where I_{SC} are the short-circuit current of the PV cell provided by the manufacturer while

the saturation current (I_s) and the reverse saturation current (I_{RS}) of the PV cell can be calculated by Eqs. (6) and (7), respectively [57].

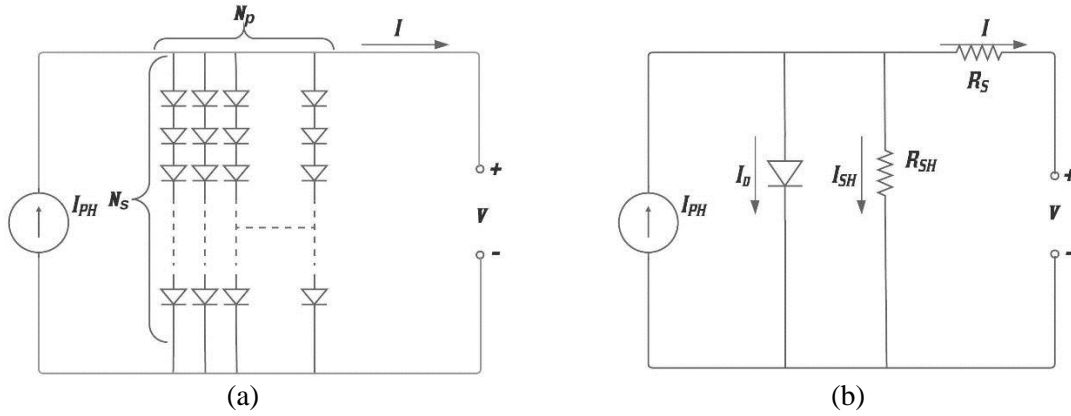


Figure 6. (a) PV cell model using diodes model connected in series and parallel; (b) Photovoltaic based on the one-diode model.

$$I = I_{PH} - I_D - I_{SH} \quad (2)$$

$$I_{PH} = N_p [I_{SC} + K_i(T_{pv} - T_{pv_STC})] \frac{G}{G_{STC}} \quad (3)$$

$$I_D = N_p I_s \left\{ \exp \left(\frac{q}{k T_{pv} n} \left(\frac{V}{N_s} + \frac{I R_s}{N_p} \right) \right) - 1 \right\} \quad (4)$$

$$I_{SH} = \frac{N_p V + N_s I_{RS}}{N_s R_{SH}} \quad (5)$$

$$I_s = I_{RS} \left(\frac{T_{pv}}{T_{pv_STC}} \right)^3 \times \exp \left(\frac{q E_g}{k n} \left(\frac{1}{T_{pv_STC}} + \frac{1}{T_{pv}} \right) \right) \quad (6)$$

$$I_{RS} = \frac{I_{SC}}{\exp \left(\frac{V_{oc}}{N_s n V_t} \right) - 1} \quad (7)$$

The characteristics and the behavior of the PV cell (Siemens SM46 PV module and Solarex MSX-60 PV module) at the STC summarized in Table 1 was used to solve Eqs. (2) to (7). The series resistance (R_s) and the shunt resistance (R_{SH}) are the causes of power loss from the PV cell which alters the slope of the I-V curve and reduces the maximum power. According to Carrero, et al. [57], the R_s and R_{SH} could be estimated corresponding with the value of V_{oc}/I_{SC} , but those values should be different for different PV cells; moreover, the R_s and R_{SH}

405 should not be constant values under different conditions of irradiation and cell temperature. In this work, the initial
 406 values of R_{SH} and R_S were defined as 54Ω and 0.54Ω suggested by Carrero, et al. [57] for Eqs. (8)(8) and (9)(9)
 407 respectively to start the iterative calculation; the Euclidean or the norm error (L^2) (Eq. (10)(10)) was being
 408 monitored during the iteration, as this error reduced as the iteration proceeds. Therefore, the values of the R_S and
 409 R_{SH} were adjusted along the iteration until the L^2 norm error stopped reducing, which was 0.1671 for Siemens
 410 SM46 PV model in this study.

$$R_{S_STC} < 0.1 \frac{V_{oc}}{I_{SC}} \quad (8)$$

$$R_{SH_STC} > 10 \frac{V_{oc}}{I_{SC}} \quad (9)$$

$$L^2 \text{ norm error} = \sqrt{\sum_{i=1}^n (u_e(i) - u_c(i))^2} \quad (10)$$

411 where the L^2 norm error represents the overall error of a dataset from a multi-point measurement, $u_e(i)$ and $u_c(i)$
 412 is the measured value and the calculated value at point i , respectively, and n is the number of data points.
 413 Based on the comparison between the simulated I-V and P-V curves and the measured data, the values of the series
 414 resistance (R_S) and the shunt resistance (R_{SH}) under different conditions of irradiation and cell temperature were
 415 obtained through iterative calculation. Hence, the new correlations of the R_{SH} as a function of the R_{SH_STC} and the
 416 ratio of the actual irradiation and the STC irradiation was developed and verified in this work as presented in Eq.
 417 (11)(11). The R_S as a function of the R_{S_STC} , the cell temperature difference and the irradiation difference between
 418 the actual value and the reference value was proposed and verified as Eq. (12)(12).

$$R_{SH} = R_{SH_STC} \frac{G}{G_{STC}} \quad (11)$$

$$R_S = R_{S_STC} + R_{s_{conT}} (T_{pv} - T_{pv_STC}) - R_{s_{conG}} (G - G_{STC}) \quad (12)$$

419 where T_{pv_STC} is 25°C , $R_{s_{conG}}$ is the constant for the irradiance dependent term, G_{STC} is $1,000 \text{ W/m}^2$.
 420 The electrical power output of the PV cell can be obtained by multiplying its output current (I) with the connected
 421 load's voltage (V). If the connected load voltage is constant such as a 12V lead acid battery, the connected load
 422 voltage may not be at the maximum power point that the PV cell can provide at that specific irradiance due to the

variation and intermittence of the solar irradiation. Practically, a maximum power point controller is installed between the PV panels and loads to increase or decrease the loads voltage meanwhile the output current changes with the varying load voltage according to its I-V characteristics, irradiance and cell's temperature, in order to extract the maximum power from the PV panel at every incoming irradiance and cells' temperature. Therefore, the maximum power output (P_{max}) was considered as the electrical power output of the PV layer (E_8) in this study and can be calculated from Eq. (13)(13).

$$P_{max} = E_8 = V_{P_max} \cdot I_{P_max} \quad (13)$$

where V_{p_max} is the load's voltage at maximum power point; I_{p_max} is the output current at maximum power point. After model validation, the PV power output is simulated using the validated model expressing I-V characteristics of the PV cells for the condition of the irradiance ranging from 0 to 1,000 W/m² and the PV cell temperature between 0 °C and 100 °C. The simulated data of the electrical power output was then fitted for the polynomial regression of the relationship between the electrical power output and the weather conditions. In this paper, the simulation was conducted in 30 minutes time-step as the electrical efficiency at each time-step may vary. The electrical efficiency (η_{elec}) was calculated from Eq. (14)(14). If the average daily efficiency was considered, the integration interval (from t_1 to t_2) was from sunrise to sunset and if the instantaneous thermal efficiency was considered, the integration interval was 30-minute.

$$\eta_{elec} = \frac{\int_{t_1}^{t_2} E_8 \, dt}{\int_{t_1}^{t_2} Irr \, dt} \quad (14)$$

where Irr is the solar irradiance as a function of time of the day (W/m²).

Table 1. Characteristics of the PV cells at STC.

Characteristics of the PV module	Siemen SM 46	Solarex MSX-60
Typical peak power (P_{MPP})	46 W	60 W
Voltage at peak power (V_{MPP})	14.6 V	17.1 V
Current at peak power (I_{MPP})	3.15 A	3.5 A
Short-circuit current (I_{sc})	3.35 A	3.8 A
Open-circuit voltage (V_{oc})	18.0 V	21.1 V

Characteristics of the PV module	Siemen SM 46	Solarex MSX-60
Temperature coefficient of open-circuit voltage (K_v)	-77 mV/°C	-80±10 mV/°C
Temperature coefficient of short-circuit current (K_i)	12 mA/°C	0.065±0.05 %/°C
the ideal factor of PV cell	1.2	1.2
Band-gap energy of semiconductor	1.16 eV	1.16 eV
Number of PV cells in series	30	36
Number of PV cells in parallel	1	1

3.2. Thermal analysis models

Two types of the PV/T collectors were studied and compared with a reference PV module in this paper, which are the PV/T collector without air gap (PV/T-no-AG) and the PV/T collector with air gap (PV/T-AG). The cross-sectional view of these two designs modelled in ANSYS Fluent is presented in Figure 7 (a) and (b) respectively. The air gap between the glass cover and the PV panel in Figure 7 (b) acts as an air insulation layer, which is favourable for thermal production. The reference PV module was modelled almost the same as the PV/T-no-AG model but without the absorber beneath the PV cell. The dimensions of all models are presented in Table 2.

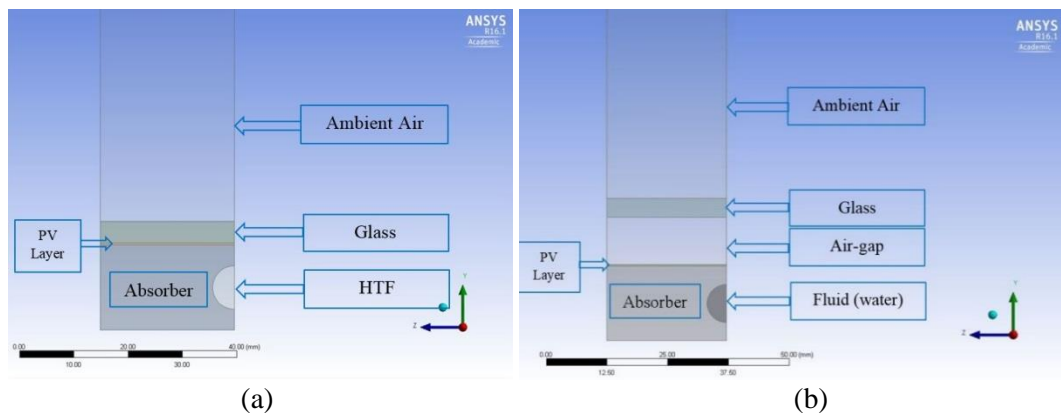


Figure 7. Cross-sectional view of the PV/T collector (a) without an air gap (b) with an air gap in ANSYS Design Modeller.

Table 2. Dimension data of the PV and PV/T collectors studied.

	PV-panel model	PV/T-no-AG model	PV/T-AG model
Ambient air thickness or Upper air thickness (Y-axis)	300 mm	300 mm	300 mm
Lower ambient air thickness (Y-axis)	300 mm	300 mm	300 mm
Glass thickness (Y-axis)	-	4 mm	4 mm
Air-gap thickness (Y-axis)	-	-	10 mm
PV layer thickness (Y-axis)	0.3 mm	0.3 mm	0.3 mm
Absorber thickness (Y-axis)	15.7 mm	15.7 mm	15.7 mm
Fluid tubes' diameter	-	8 mm	8 mm
All components' length (X-axis)	1830 mm	1830 mm	1830 mm
Cut models' width (Z-axis)	24.65 mm	24.65 mm	24.65 mm
	symmetry	symmetry	symmetry
Full model width (Z-axis)	986 mm	986 mm	986 mm
Length between 2 fluid tubes	-	49.3 mm	49.3 mm

454

455 The energy balance is dominated by heat conduction in the solid elements including glass cover, PV cells and
 456 absorber (including tubes), as expressed in Eq. [\(15\)](#).

$$\rho_m \delta_m C_m \frac{dT_m}{dt} = k_m \delta_m \left(\frac{\partial^2 T_m(x, y, z)}{\partial x^2} + \frac{\partial^2 T_m(x, y, z)}{\partial y^2} + \frac{\partial^2 T_m(x, y, z)}{\partial z^2} \right) + \sum Q_m \quad (15)$$

457 where the subscriber 'm' is replaced by different symbols to represent different elements, e.g. 'g' when the glass
 458 layer is under consideration, or 'pv' when the PV-layer is discussed, or 'ab' for the case of the absorber layer; $\sum Q$
 459 is the summation of different heat sources for each layer. For all different models studied, the energy balance of
 460 the single glass cover ($\sum Q_g$) for example expressed in Eq. [\(16\)](#) includes the solar radiation to the glass cover
 461 Q_1 (Eq. [\(17\)](#)), the sky radiation to the glass cover Q_2 (Eq. [\(18\)](#)), the convective heat from ambient air to
 462 the glass Q_3 (Eq. [\(19\)](#)), the radiative heat from the glass to PV cell Q_4 (Eq. [\(20\)](#)), and the radiative heat

463 from the glass to ground Q_5 (Eq. [\(21\)](#)~~(21)~~). For the PV/T-AG model, the convective heat between the glass and
 464 the PV cell according to natural convection in the air layer Q_{6_a} was calculated in (Eq. [\(22\)](#)~~(22)~~) and replace the
 465 Q_6 in Eq. [\(16\)](#)~~(16)~~; whereas, for the PV/T-no-AG and the PV panel models, the conductive heat transfer between
 466 the glass and PV surface Q_{6_b} (Eq. [\(23\)](#)~~(23)~~) was used to replace the Q_6 in Eq. [\(14\)](#)~~(14)~~. Note that the positive signs
 467 in Eq. [\(16\)](#)~~(16)~~ mean the heat is absorbed by the layer envisaged and minus signs represent the heat released from
 468 the layer envisaged.

$$\Sigma Q_g = Q_1 + Q_2 + Q_3 - Q_4 - Q_5 - Q_6 \quad (16)$$

$$Q_1 = \alpha_g G \quad (17)$$

$$Q_2 = \varepsilon_g \sigma (T_{sky}^4 - T_g^4) \quad (18)$$

$$Q_3 = h_{wi}(T_a - T_g) \quad (19)$$

$$Q_4 = h_{ray,g \rightarrow pv}(T_g - T_{pv}); h_{ray,g \rightarrow pv} = \frac{\sigma(T_g^2 + T_{pv}^2)(T_g + T_{pv})}{\frac{1}{\varepsilon_{pv}} + \frac{1}{\varepsilon_g} - 1} \quad (20)$$

$$Q_5 = \varepsilon_g \sigma (T_g^4 - T_{gr}^4) \quad (21)$$

$$Q_{6_a} = h_{conv,g \rightarrow pv}(T_g - T_{pv}) \quad (22)$$

$$Q_{6_b} = h_{cond,g \rightarrow pv}(T_g - T_{pv}); \quad (23)$$

469 Sky temperature can be approximately calculated by using Eq. [\(24\)](#)~~(24)~~ [58] where L_0 , A , B and C are obtained
 470 from Eqs. [\(25\)](#)~~(25)~~ to [\(28\)](#)~~(28)~~ respectively with the ambient vapour pressure (P_v) calculated by Eq. [\(29\)](#)~~(29)~~ [59].
 471 Ground temperature is approximately 2 °C lower than ambient temperature [60].

$$T_{sky} = \left(\frac{L_0(1+0.01A) + \frac{BC(8-N_e)}{8}}{\sigma} \right)^{0.25} \quad (24)$$

$$L_0 = 3.6(T_a - 273.15) + 231 \quad (25)$$

$$A = 10.1 \ln(P_v) - 12.3 \quad (26)$$

$$B = 1.7(T_a - 273.15) + 107 \quad (27)$$

$$C = -0.22 \ln(P_v) + 1.25 \quad (28)$$

$$P_v = 611.21 \exp \left\{ \left(18.678 - \frac{T_a}{234.5} \right) \left(\frac{T_a}{257.14 + T_a} \right) \right\} \quad (29)$$

485 To accurately calculate Q_{6_a} in Eq. (22)(22), natural convection theory is considered in the air-gap layer of the
 486 PV/T-AG and $h_{conv, g \rightarrow pv}$ is obtained from Eq. (30)(30) where the Nusselt number (Nu_{gap}) can be calculated by Eq.
 487 (31)(31), where θ is the tilt angles of the PV/T-AG which is valid from 0° to 75° , Ra is the Rayleigh number
 488 defined as the production of Grashof Number (Gr) and the Prandtl number (Pr).

$$h_{conv, g \rightarrow pv} = \frac{Nu_{gap} k_{gap}}{\delta_{gap}} \quad (30)$$

$$Nu_{gap} = 1 + 1.44 \left[1 - \frac{1708}{Ra \delta_a \cos \theta} \right] \left[1 - \frac{1708 (\sin \theta)^{1.66}}{Ra \delta_a \cos \theta} \right] + \left[\frac{(Ra \delta_a \sin \theta)^{0.33}}{5830} - 1 \right] \quad (31)$$

489 For the pv layer of all three models, the transient energy balance can be analysed using Eq.(15)(15) with PV cell
 490 material properties and ΣQ_{pv} given in Eq. (32)(32). Q_7 is the heat absorbed by PV layer from the solar irradiance
 491 which can be calculated by Eq.(33)(33); E_8 is the electrical power production in the PV layer which is described
 492 in the previous section and Q_9 is the conductive heat from the PV layer to the absorber layer as presented in
 493 Eq.(34)(34) with its thermal contact conductance coefficient $h_{cond, pv \rightarrow abs}$ calculated from Eq. (35)(35).

$$\Sigma Q_{pv} = Q_4 + Q_5 + Q_7 - E_8 - Q_9 \quad (32)$$

$$Q_7 = \alpha_{pv} \tau_g G \quad (33)$$

$$Q_9 = h_{cond, pv \rightarrow abs} (T_{pv} - T_{abs}); \quad (34)$$

$$h_{cond, pv \rightarrow abs} = \frac{1}{\frac{\delta_{pv}}{k_{pv}} + \frac{\delta_{abs}}{k_{abs}}} \quad (35)$$

494 The energy balance in the absorber layer of the PV/T-no-AG and PV/T-AG models can be expressed as shown in
 495 Eq. (36)(36) where Q_{10} is the convective heat transfer from the absorber layer to the HTF (Eq. (37)(37)). For the
 496 PV panel model where there is no HTF, Q_{10} represents the convective heat transfer from the absorber to the ambient
 497 air (Eq. (38)(38)). The material properties used in the models are presented in Table 3Table 3.

$$\Sigma Q_{abs} = Q_9 - Q_{10} \quad (36)$$

$$Q_{10_a} = h_{abs-HTF} (T_{abs} - T_{HTF}) \quad (37)$$

$$Q_{10_b} = h_{wi} (T_{abs} - T_a) \quad (38)$$

Table 3. The material properties used in the PV and PV/T collectors models.

Material properties	Glass	PV cell	Absorber (Aluminium)	Air	HTF (water)
Absorption coefficient, α (-)	0.05	0.8	-	-	-
Density, ρ (kg/m ³)	2,200	700	2719	1.225	998.2
Emissivity, ε (-)	0.88	-	-	-	-
Specific heat capacity, C_p (J/(kg·K))	670	900	871	1,006	4,182
Thermal conductivity, k (W/(m·K))	0.9	144	202.4	0.0242	0.6
Transmistivity, τ (-)	0.91	-	-	-	-
Viscosity, (kg/m·s)	-	-	-	1.7894e-05	0.001003

499 Note: Only the relevent properties of the materials used in the models are presented in the table.

500 In the fluid regions including the ambient air and HTF, the continuity, energy, momentum and turbulence equations
501 were treated using the finite volume approach to computationally solve the transport equations in Eq. (39)(39) in
502 ANSYS Fluent, where $\phi = 1$ for continuity equation, $\phi = \vec{V}$ for momentum equations, and $\phi = h$ for energy equation
503 [61]. The first term on the left-hand side of Eq. (39)(39) is the unsteady term, the second term is the convective
504 term, the first term on the right-hand side is the diffusion term and the last term on the right-hand side is the
505 generation term.

$$\frac{\partial}{\partial t} \int_V \rho \phi dV - \oint_A \rho \phi \vec{V} \cdot d\mathbf{A} = \oint_A \Gamma_\phi \nabla \phi \cdot d\mathbf{A} + \int_V S_\phi dV \quad (39)$$

506 Turbulent flow by using SST k-omega (2 equations) model was chosen along with the viscous heating option to
507 get more accurate solutions especially in viscous heating cases such as the heat transfer between solid and fluid
508 zones. Low-Re Corrections was selected in the cases of low Reynolds number flow. There was a big temperature
509 gradient along the PV/T panel from the inlet side to the outlet side, so the volume weighted average of the simulated

PV temperature was used in this work. To reduce the computational time, ground and sky was treated as source terms in the unit of W/m³.

In this study, the useful thermal efficiency (η_{th}) was considered and it was calculated from Eq. (40). Note that if the temperature of the HTF could not reach the setting temperatures, the pump would not operate and the mass flow rate would be zero, in this instance, the instantaneous thermal efficiency would be zero based on the Eq. (40), even though the temperature of the HTF raised inside the PV/T. Again, if the overall average thermal efficiency was considered, the integration interval (from t_1 to t_2) was the time from sunrise to sunset; the integration interval was 30 minute for the calculation of the instantaneous thermal efficiency.

$$\eta_{th} = \frac{\int_{t_1}^{t_2} \dot{m} C_{P_HTF} (T_{out} - T_{in}) dt}{\int_{t_1}^{t_2} Irr dt} \quad (40)$$

where \dot{m} is the mass flow rate of the HTF out from 1 m² PV/T collectors; C_{P_HTF} is the specific heat capacity of the HTF ; T_{out} is the output temperature of the HTF from the PV/T; T_{in} is the input temperature of the HTF to the PV/T.

4. Results and discussion

4.1. Model validation

Using the developed correlations of R_{SH} and R_S in Eqs. (11) and (12), the calculated I-V characteristic under different conditions satisfactorily agree with the datasheets of the Siemens SM46 PV module and the Solarex MSX-60 PV module as shown in Figure 8 and Figure 9 respectively.

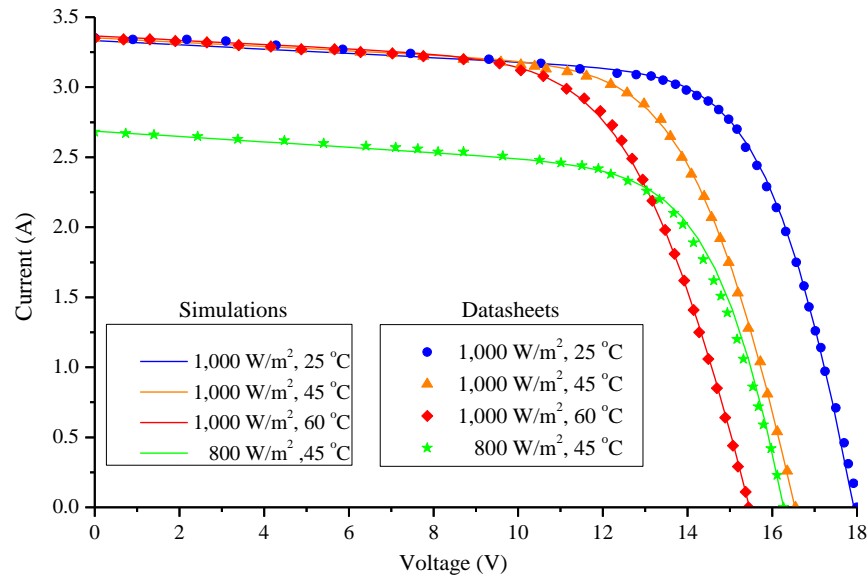


Figure 8. Verification of simulation results with datasheet of I-V characteristics in different conditions for Siemens SM46 PV module.

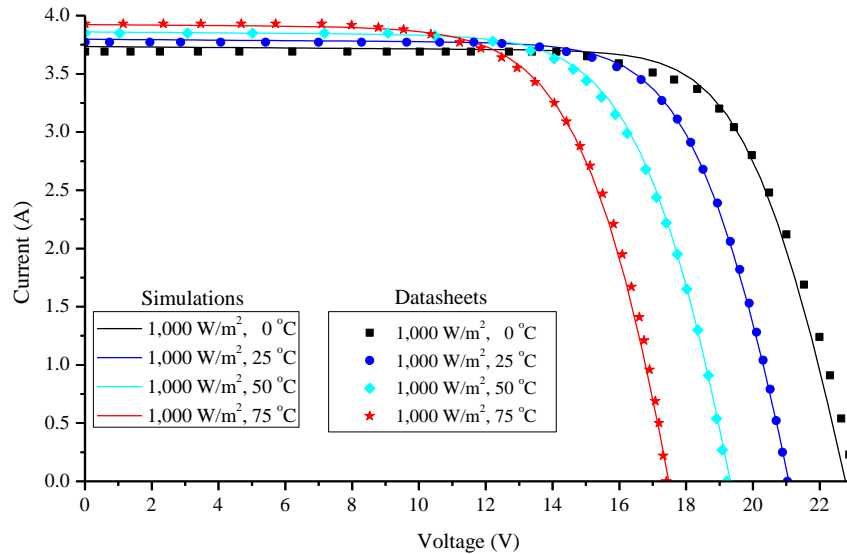
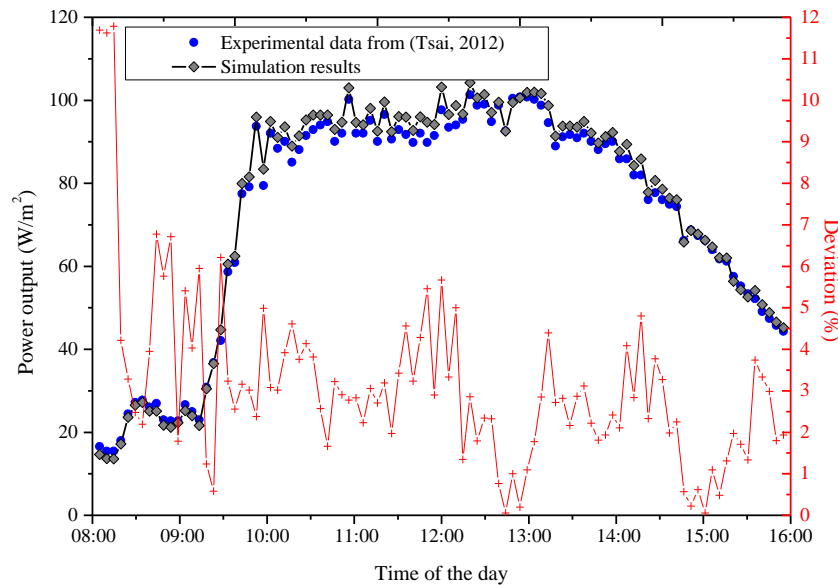


Figure 9. Verification of simulation results with datasheet of I-V characteristics in different conditions for Solarex MSX-60 PV module.

Compared to using the R_S and R_{SH} value from the calculation of V_{OC}/I_{SC} , using these modified equations of R_S and R_{SH} made the average error of electrical power output at MPP reduce from 1.59% to 0.52% for Siemens SM46 PV module, from 1.50% to 1.04% for Solarex MSX-60 PV module. The reduction of the average error over the low PV cell temperature range studied are insignificant, the errors at medium to high PV cell temperatures are substantially decreased. For example, the error of the PV power outputs operating at 60 °C at MPP reduces from

555 3.57% to 0.85% for Siemens SM46 PV module. Therefore, when the PV cell is used at medium to high
556 temperatures, the modified correlations in Eqs. (11)(44) and (12)(42) are worth applying for better accuracy.
557 The developed PV model that uses the modified equations of R_S and R_{SH} was also validated by using one-day real
558 weather data and the experimental data of electrical power output from Ref. [56]. ~~Figure 10~~Figure 40 shows the
559 great agreement between the simulated PV electrical power output at MPP and the measured data reported in Ref.
560 [56], the average error is 2.55% with 0.66 W average absolute difference. To validate the thermal analysis model,
561 the simulation results of the PV cell temperatures was compared with the measured data provided by Ref. [56] (in
562 ~~Figure 11~~Figure 44), there was an average relative error of 4.57% with an average absolute difference of 2.03 K,
563 that implies that the PV model coupled with the CFD model developed in this work is reasonably reliable.



564

565 Figure 10. PV Electrical power output between the measured data from [56] of and the simulation results.

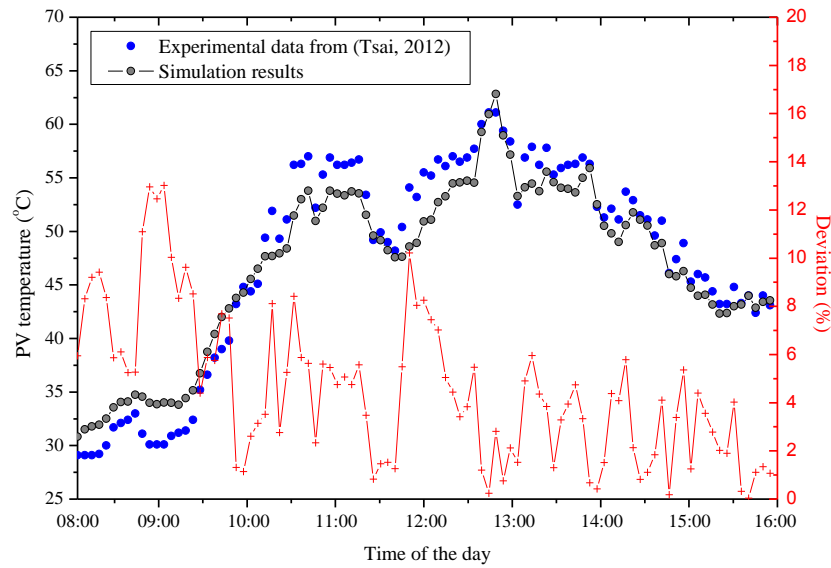


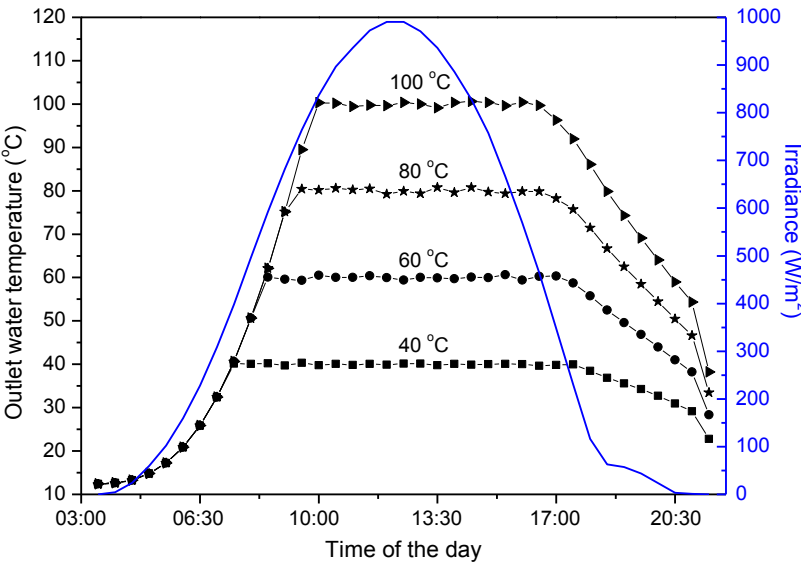
Figure 11. PV temperatures between the measured data from [56] and the simulated volume-weighted average temperature.

4.2. PV/T collector simulation results

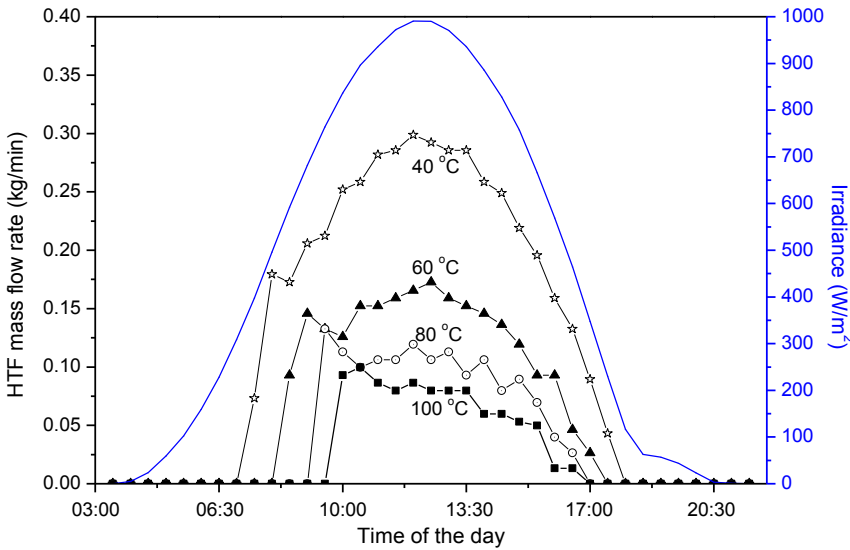
The weather data of a sunny summer day (June 28th 2005) in Newcastle Upon Tyne are used as a case study to explore the potential hot water production by the studied PV/T collector. The water outlet temperature was preset at four targeted points, 40 °C, 60 °C, 80 °C and 100 °C, which was achieved by varying the water flow velocity so that to cope with the desorption heat requirement of the thermochemical sorption storage unit.

The half-hourly variation profile of the hot water output temperature at different preset points and the corresponding solar irradiation is shown in [Figure 12](#) for the PV/T with air gap (PV/T-AG). The calculation started when solar radiation was firstly available on the chosen days. The inlet water temperature was assumed to be the same temperature as the ambient temperature (around 14 °C). Solar irradiance was increasing in the morning, but it was not intense enough to heat up the water in the absorber tube to the targeted temperature levels until 07:00 ~10:00 am in summer, depending on different targets. Before that it was assumed a stagnation condition of the water loop, i.e. no fluid flowing in the collector, until the stationary water was heated up to the targeted temperature resulting in the uniform increasing temperature over the PV/T panel area. Since then, the

583 water circulation started and the flow rate was afterwards adjusted according to the varying irradiation as shown
584 in [Figure 13](#)[Figure-13](#).



585
586 Figure 12. The water output temperature at different targeted levels from the PV/T with airgap collector on a
587 sunny summer day in Newcastle upon Tyne, UK.



588
589 Figure 13. The mass flow rate of the output fluid at different targeted temperature from the PV/T with air gap
590 models on a sunny summer day in Newcastle upon Tyne, UK.

591
592 The lower targeted output temperature, the higher water mass flow rate allowed ([Figure 13](#)[Figure-13](#)) and the
593 higher average thermal efficiency obtained as well as electrical efficiency ([Figure 14](#)[Figure-14](#)), i.e. higher overall

energy efficiency of the PV/T collector, because the lower PV/T temperature means lower heat loss and it is beneficial for electrical power generation. It is noted that, when there was a stagnation situation of the water loop with the water temperature inside the PV/T increasing while it was absorbing energy from the sun, the useful thermal efficiency was considered to be zero because there was no thermal energy carried out of the PV/T panel. The higher the set output temperature, the longer time it waited before the water pump started working. The moment when the water pump started, the average water temperature in the PV/T collector as a whole reached the targeted level as there was a nearly uniform temperature all over the collector in a stagnation condition. That led to the highest instantaneous useful thermal efficiency and a drop of instantaneous electrical efficiency, and this phenomenon is more obvious for the cases requiring higher temperature water output, e.g. 80 °C and 100 °C curves in [Figure 14](#). Once the water flowed and the fresh water at ambient temperature came into the absorber tubes, the average water temperature inside the PV/T collector dropped and the water flow rate in the next time step had to be adjusted lower accordingly to be able to deliver the targeted high temperature water output. Afterwards, the water flow rate increased again in the 40 °C and 60 °C curves as the increasing irradiance was intense enough to produce qualified water with relatively flat profile of thermal efficiency during the daytime; otherwise, for the 80 °C and 100 °C curves, the flow rate and the thermal efficiency decreased in a zig-zag pattern as the time went on.

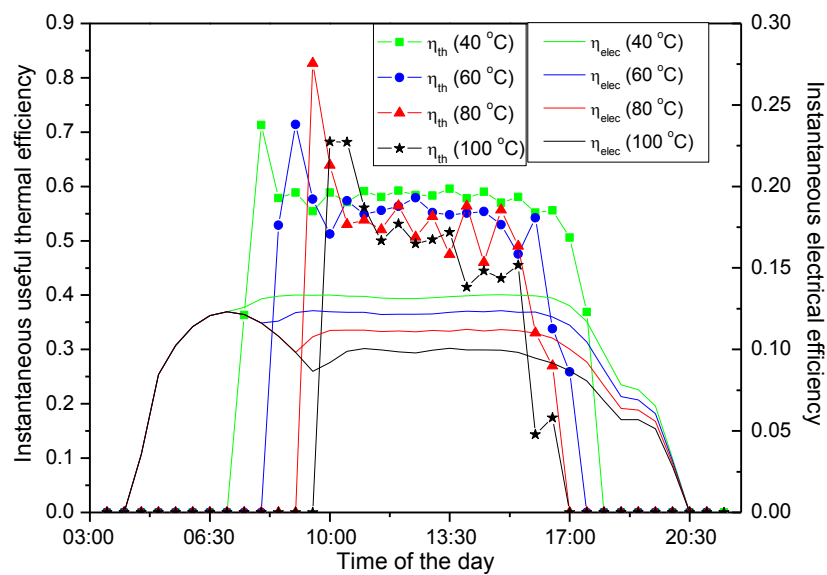
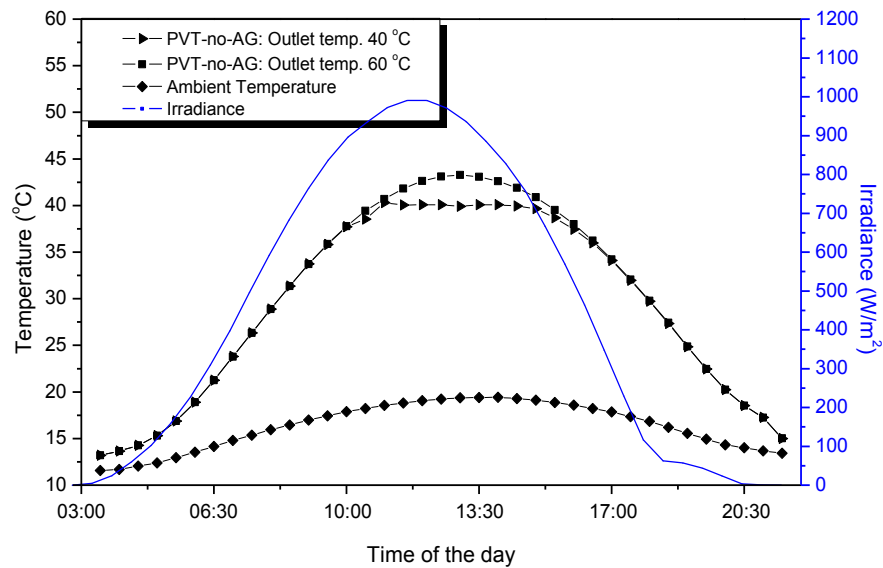


Figure 14. Instantaneous thermal efficiency and electrical efficiency of the PV/T collector with air gap.

613

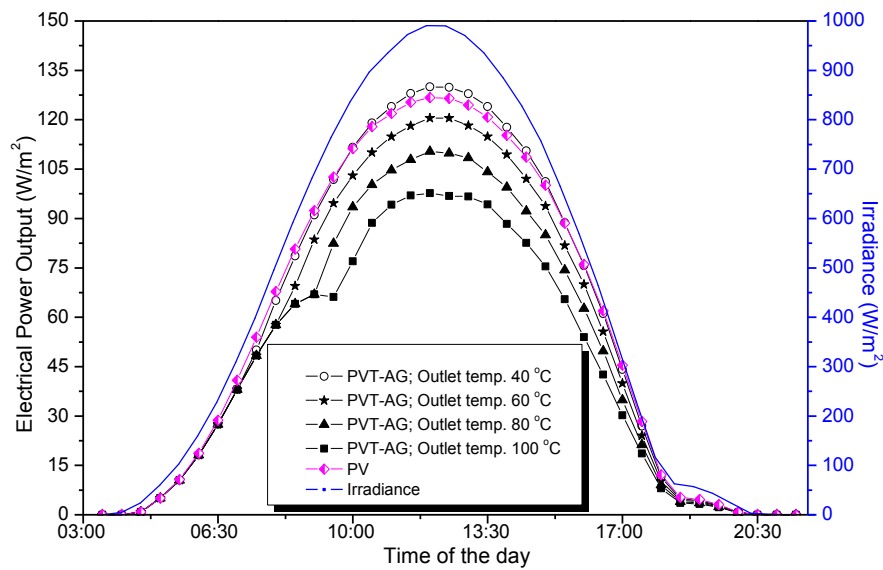
614 The half-hourly variation profile of the water output temperature at different preset points for the PV/T collector
615 without air gap (PV/T-no-AG) is shown in [Figure 15](#)~~Figure 15~~. It is not surprising to learn that under the given
616 climatic condition, the water temperature of the PV/T-no-AG type cannot be heated higher than about 43 °C even
617 in a stagnation condition all day long. The wind speed and ambient temperature can have considerable influence
618 on the effective heat delivered, especially in the cold region even though in the sunny days the heat loss to the
619 ambient could be much more compared to the PV/T-AG type. Therefore, it can be concluded that the addition of
620 air insulation layer is significant to enhance thermal energy output of the PV/T collector especially for the weather
621 conditions similar to that in Newcastle upon Tyne.



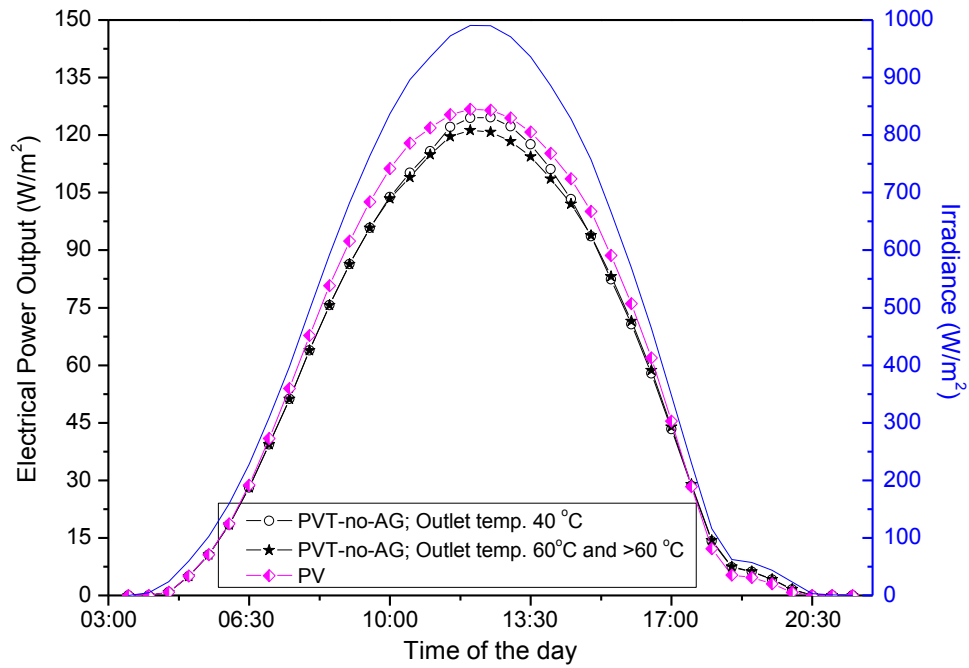
622

623 Figure 15. The water output temperature at different targeted levels from the PV/T without airgap collectors on a
624 sunny summer day in Newcastle upon Tyne, UK.

Electrical power production from the PV/T-AG collector and PV/T-no-AG collector is shown in Figure 16 in comparison with the production from the PV panel. The 40 °C curve of the PV/T-AG collector is closer to the reference PV curve, and has a slightly higher maximum power output during the mid-day than that of the reference PV curve; whereas, the electrical power gradually reduces with the increasing water output temperature, as the maximum power output on the 100 °C curve is about 23% lower than that of the reference PV curve. In general, the normal PV/T collector even without air gap design would be expected to produce more electrical power than the PV-only panel. However, in this work, the PV/T-no-AG collector operated under a stagnation condition of the water loop most of the time, which in fact to some extent hampered the heat dissipation and increased the PV cell temperature, as shown in Figure 15. Because higher PV cell temperature has detrimental effect on electrical power generation, and the average PV cell temperature of the PV/T-no-AG collector is always higher than the reference PV panel, which explains the less production from the PV/T-no-AG collector than that of the reference PV panel. With the same reason, the power output curve of the reference PV panel is in between the 40 °C and 60 °C curves for the PV/T-AG collector, it is echoed by the comparison between the PV cell temperature curves in Figure 17. It also implies that if the electrical generation is of primary, the PV cell temperature should be kept lower than 40 °C to have tangible improvement of electrical efficiency.



(a)



(b)

Figure 16. The electrical power output from (a) the PV/T with airgap; (b) the PV/T without airgap models on a sunny summer day in Newcastle upon Tyne, UK.

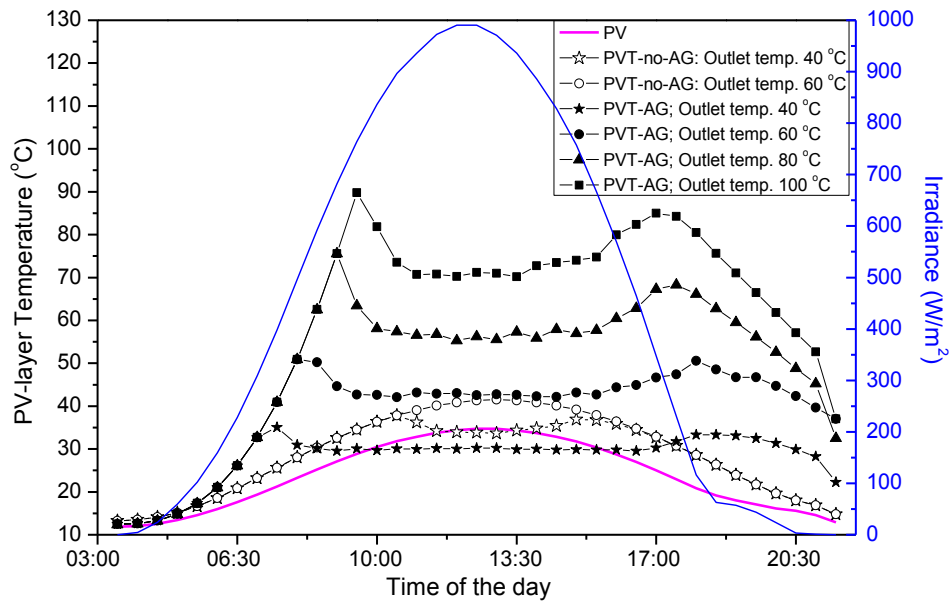


Figure 17. The PV-cell temperature of the PV/T collectors on a sunny summer day in Newcastle upon Tyne, UK.

4.3. Potential application integrated with thermal energy storage

(1) Domestic hot water use with water storage tank

652 For a typical UK household with approximately 30 m² rooftop area (a typical 4kWp of PV installation size) [62],
 653 the size of the PV/T-AG system installed at the optimum tilted angle was investigated to explore its potential of
 654 meeting the household hot water demand. The simulation results of the amount of water output at different
 655 temperature levels and the energy conversion efficiency by using the studied PV/T-AG collector was present in
 656 [Table 4](#)~~Table-4~~. On a typical sunny day in June in Newcastle, the amount of hot water production is from around
 657 28 L/(day·m²) to 133 L/(day·m²) with the overall energy conversion efficiency from 45% to 66%, as the required
 658 output temperature ranging from 100 °C to 40 °C. For a sunny autumn day in September, the studied PV/T-AG
 659 collector can produce 19~98 L/(day·m²) hot water depending on different required output temperature, with the
 660 overall energy conversion efficiency of 36%~59%, which is around 11%~18% lower than the efficiency obtained
 661 in summer.
 662 Ref. [49] reported the mean daily hot water consumption of a single dwelling ranges from 98.44 litres in July to
 663 133.16 litres in December in the UK. [Table 5](#)~~Table-5~~ lists the monthly usage in each month and the required
 664 installation area of PV/T-AG collector, based on the following consideration and assumption: the months of June
 665 and July are considered to have similar weather conditions, i.e. the simulation data for the month June is also used
 666 for performance calculation in July; while the spring and autumn months including August, September, October,
 667 March, April and May have similar weather conditions; the typical number of mostly sunny, partly sunny or clear
 668 days in Newcastle is 10 days each month, and the hot water is only produced during these days; the hot water is
 669 delivered at 60 °C (i.e. the water outlet temperature); the water storage tank is assumed to have sufficient volume
 670 to store the solar thermal energy available for 10 days for the whole month usage; it is assumed to have negligible
 671 energy storage loss due to good insulation. Because of low irradiance, low ambient temperature and few sunshine
 672 hours during the winter time in Newcastle, the PV/T collector is not able to deliver useful thermal energy from
 673 November until February. Therefore, in order to satisfy the hot water demand from March to October with 100%

674 solar energy fraction, at least 7.76 m² of the PV/T-AG collector need to be installed for a single household. In the
 675 meantime, the total electricity output from March to October is around 500 kWh.

676 Table 4. Performance comparison between reference PV and PVT-AG collector under different conditions.

	Sunny summer day (28 th June 2005)					Sunny autumn day (4 th September 2005)				
Type of Model	T _{w,o} (°C)	m _w (liter/day/m ²)	Ave. η _{elec} (%)	Ave. η _{th} (%)	Total η (%)	T _{w,o} (°C)	m _w (kg/day m ²)	Ave. η _{elec} (%)	Ave. η _{th} (%)	Total η (%)
PV	-	-	12.97	-	12.97	-	-	12.09	-	12.09
PVT with air gap	100.0	27.97	9.88	34.79	44.68	100.0	18.00	9.07	27.40	36.47
	80.0	42.00	10.96	40.40	51.36	80.0	28.45	10.76	33.54	44.30
	60.0	68.18	12.03	46.56	58.59	60.0	49.03	11.06	40.56	51.62
	40.0	132.87	12.99	53.22	66.21	40.0	97.78	11.98	46.82	58.80

677

678 (2) Integration with thermochemical sorption storage

679 The potential storage capacity of the thermochemical storage system is explored by exemplifying 30 m² installation
 680 area of the PV/T-AG collectors, when the hot water output is required to be at 100 °C. [Table 5](#) lists the
 681 average monthly data of the operating conditions such as the water sources temperature and the ambient
 682 temperature as well as the required desorption temperature (T_{des}) with inclusion of the 5 °C equilibrium drop,
 683 which is only in the range of 79 °C to 87 °C. Therefore, the hot water temperature of 100 °C would be sufficiently
 684 high to make sure the proper desorption and energy charging process. The total amount of the solar heat that can
 685 be stored from March to October is around 3,522.55 GJ, which is adequate to cover the hot water demand of
 686 around 3,058.74 GJ [26] from November to February. In fact, the collector area can accordingly reduce to 26 m²
 687 but still fully meet the requirement. It is noted that zero energy loss has been assumed for the thermochemical

sorption system, but the detailed design and analysis of the thermochemical sorption system is out of the scope of this work and will be presented in the future works.

Combined the results in the first application case for domestic hot water use in [Table 5](#) and the electricity generation data shown in [Table 6](#), it can be expected that such an integrated system with 26 m² PV/T-AG collectors can fully satisfy the hot water demand of a single household all year around with 100% renewable sources, while the total solar electricity generation could be around 1365 kWh. In fact, the actual total annual electricity output could be higher than this value, because even in the deep winter when no useful hot water could be produced, there is still electricity output, but the simulation results presented in this work does not include the electricity generation in the winter time. It was reported that the average electricity consumption per British household without electric heating was around 3638 kWh [63]. That means at least half of the total electricity consumption can be met by renewable generation by using this integrated system.

Table 5. The potential performance of two applications of the PVT-AG collector

Month	T _{w,cold} (°C)	Avg. hot water consumption (m ³ /month)	Hot water (60 °C) energy demand (GJ/month)	Required PV/T installation area for 60 °C hot water demand (m ²)	T _{amb} (°C)	T _{des} of SrCl ₂ (8/1) (°C)	Storable thermal energy (GJ/month) based on 30 m ² installation area with T _{w,o} = 100°C
Jan	9.62	3.62	760.60	-	3.0	-	0
Feb	9.32	3.49	739.56	-	3.1	-	0
Mar	10.70	3.90	817.23	7.76	5.1	74.13	521.85
Apr	13.70	3.44	670.35	6.86	7.1	75.88	478.09
May	15.32	3.81	722.47	7.59	9.9	78.32	417.08
Jun	17.26	3.50	629.80	5.01	13.0	80.99	525.48
Jul	19.33	3.05	515.19	4.37	14.5	82.28	477.09
Aug	18.67	3.27	566.56	6.52	14.4	82.19	320.31
Sep	17.88	3.38	598.07	6.73	12.6	80.65	358.82

Month	T_{w_cold} (°C)	Avg. hot water consumption (m ³ /month)	Hot water (60 °C) energy demand (GJ/month)	Required PV/T installation area for 60 °C hot water demand (m ²)	T_{amb} (°C)	T_{des} of SrCl ₂ (8/1) (°C)	Storable thermal energy (GJ/month) based on 30 m ² installation area with $T_{w,o} = 100^{\circ}\text{C}$
Oct	15.55	3.83	717.65	7.63	9.6	78.05	423.83
Nov	12.22	3.84	739.54	-	6.0	-	0
Dec	10.51	4.13	819.04	-	3.8	-	0

700

701 Table 6. Electricity output of the PVT-AG collector.

Outlet Temp. (°C)	Autumn & spring production (March, April, May, August, September, October)		Summer production (June, July)		Annual total (kWh)
	kWh/(m ² · day)	per 30m ² PVT 60 days in total (kWh)	kWh/(m ² · day)	per 30m ² PVT 20 days in total (kWh)	
100	0.605	1089.0	0.810	486.0	1575.0
80	0.672	1209.6	0.899	539.4	1749.0
60	0.737	1326.6	0.987	592.2	1918.0
40	0.799	1438.2	1.066	639.6	2077.8

702

703 Considering the energy quality and the increasing electricity demand for wider electrification and electric vehicles,
704 electricity may be still the primary desire for many households. The results generated in this work evidence the
705 conflict between the electrical and thermal performance of the PV/T system, i.e. the electrical efficiency dropped
706 from 12-13% to 9-10% if the heat output temperature was 40 °C compared with the case of 100 °C, namely, with
707 the goal of fully covering the domestic hot water demand over a year, the electric output is depressed. Therefore,
708 a trade-off between the electrical output and the temperature of heat output is needed depending on the end-user
709 needs. To increase the electrical output, obviously the PV/T collector temperature has to be reduced. On the other
710 hand, apart from the SrCl₂-NH₃ working pair, in fact there are countless number of reactive halide salts can be
711 used in thermochemical sorption system to recover a wide temperature range of thermal energy, with great

712 potential for various heating applications. For example, the $\text{BaCl}_2\text{-NH}_3$ working pair requires relatively lower
713 desorption temperature than the $\text{SrCl}_2\text{-NH}_3$ pair, and its adsorption heat can be effectively used for low temperature
714 heating facilities, e.g. floor heating or fan convector using 35 °C as feed temperature and 25 °C as return
715 temperature, instead of high temperature heating considered in this work. Such an operating condition is more
716 desirable for the purpose of improving electric efficiency and output. It would be worth more effort to evaluate
717 the performance of thermochemical sorption systems using different working pairs with the optimal system
718 configuration and suitable and effective applications for each working pair to explore the maximum potential of
719 such an innovative integration.

720 There is another interesting integration to be explored further for more cost-effective and flexible utilisation of
721 solar energy. The work [64] proposed and studied a novel integrated thermochemical sorption system combining
722 a compressor/expander with a sorption cycle, and it can be driven by ultra-low grade heat (30~100 °C) for
723 simultaneous electrical energy storage and thermal energy storage. During the energy charging process, the ultra-
724 low grade heat is used for desorption with the aid of working fluid compression process powered by electricity
725 through the compressor. In this case, both heat and electricity can be stored in form of chemical potential energy
726 for long-term and zero-loss storage. During the energy discharging process, the stored energy can be used to
727 flexibly deliver heating, or cooling, or electric output, depending on the end user demand. The most interesting
728 point of the integration between this new sorption system and the PV/T system is, this sorption storage system can
729 operate with high temperature heat input and small amount of electricity, or low temperature heat input with larger
730 amount of electricity, which perfectly match with the performance characteristic of the PV/T system. Such a highly
731 integrated system provides the desirable function equivalent to the combination of battery and thermal energy
732 storage, and also maximises the flexibility of solar energy recovery and utilisation. In-depth investigation and
733 detailed results of its potential performance will be reported in our next work.

734

735 **5. Conclusion**

736 This work numerically demonstrated the feasibility of the hybrid solar photovoltaic-thermal collector for domestic
737 hot water application and the integration with thermochemical sorption system for seasonal energy storage. Instead
738 of using the simplified model of electrical power generation in majority of research works on the PV/T collectors,

739 a detailed model based on the one-diode model and the modified equations of R_{SH} and R_S were developed to couple
 740 with a CFD model for performance prediction of both thermal power and electrical power generation under various
 741 operating conditions.

742 The model validation suggests that the modified equations of R_{SH} and R_S proposed in this work as a function of
 743 irradiance and cell's temperature can improve the simulation accuracy under a wider range of operating conditions,
 744 especially for the cases with high PV cell temperature, compared to that resulted from assuming constant internal
 745 series resistances. The average error of the electrical power outputs at MPP can be considerably decreased from
 746 3.57% to 0.85% for Siemens SM46 PV module operating at 60 °C, from 2.40% to 0.83% for Solarex MSX-60
 747 module operating at 75 °C. In the meantime, the average error of the PV cell's temperature can be also improved
 748 to 0.63%.

749 Two types of PV/T collectors, with and without air gap, were simulated to see their performances under the high-
 750 latitude weather conditions, while the mass flow rate of the water loop was controlled and adjusted to obtain the
 751 hot water that leaves the PV/T collector at the targeted temperatures (from 60 to 100 °C) for specific applications.
 752 In Newcastle upon Tyne, to achieve the targeted heat output temperature of 60 °C in a sunny summer day based
 753 on 1 m² PV/T panel, the PV/T-AG collector has to operate at the HTF mass flow rate of lower than 0.175 kg/min
 754 and produces 68.18 litre/day/m² hot water with a thermal efficiency of around 47%, while the electrical efficiency
 755 is 12.03%, which is 0.94% lower than the PV panel. In contrast, the PV/T-no-AG collector produces heat output
 756 at no higher than about 43 °C under the same conditions.

757 Both thermal efficiency and electrical efficiency of the PV/T-AG collector is increased when it operates with lower
 758 outlet HTF temperature, because of less heat loss caused by the smaller temperature difference between the PV/T
 759 temperature and the ambient air and the positive effect of lower PV cell temperature on the electrical efficiency.

760 The PV/T-AG can produce hot water at 100 °C in sunny summer days with lower total efficiency (44.68%)
 761 resulting from the high temperature of the panel leading to high heat loss and low electrical efficiency (9.88%).
 762 The comparative results suggest that the air-gap layer has significant effect to prevent massive heat loss especially
 763 in cold climate region where the ambient temperature is low almost all year round.

764 The application case studies demonstrated that (1) an installation of 7.76 m² air-gap PV/T collector can satisfy hot
 765 water demand (at 60 °C) of an ordinary single household in the city of Newcastle upon Tyne from March to

October; (2) integrated with an installation of 26 m² air-gap PV/T collector, the thermochemical sorption system using the working pair of SrCl₂-NH₃ can seasonally store and shift the heat load to cover the hot water demand from November to February. Such an integrated system can fully satisfy the hot water demand all year around and half of the annual electricity consumption for a single household. By taking the longevity of the collector into account, further studies on the life cycle analysis for high temperatures operation should be conducted.

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